

# Status of extraction of QGP transport parameters

Björn Schenke

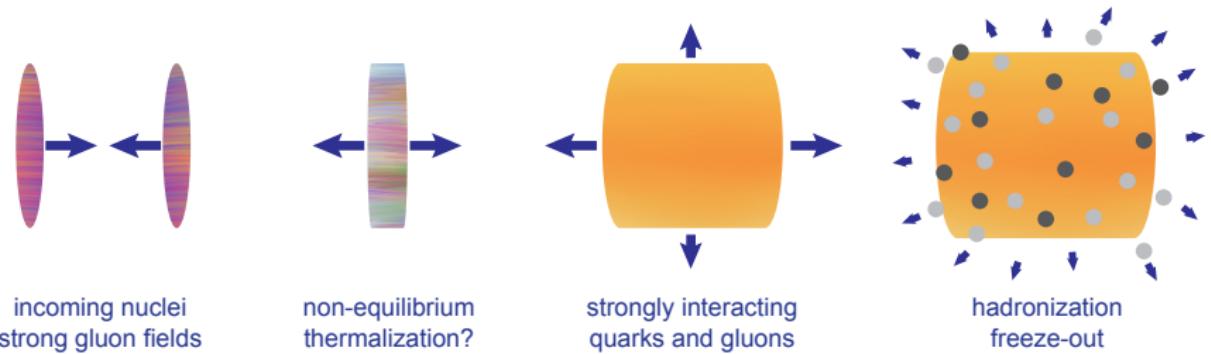
Physics Department, Brookhaven National Laboratory, Upton, NY, USA

June 28 2013

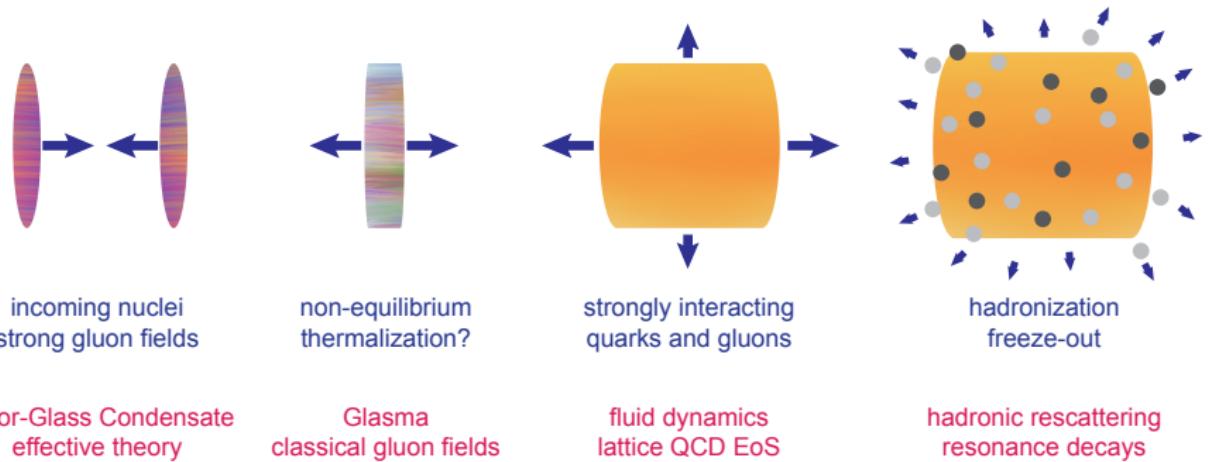
2013 RHIC & AGS  
Annual Users' Meeting

BNL, Upton, NY

# Introduction - Heavy-Ion collisions

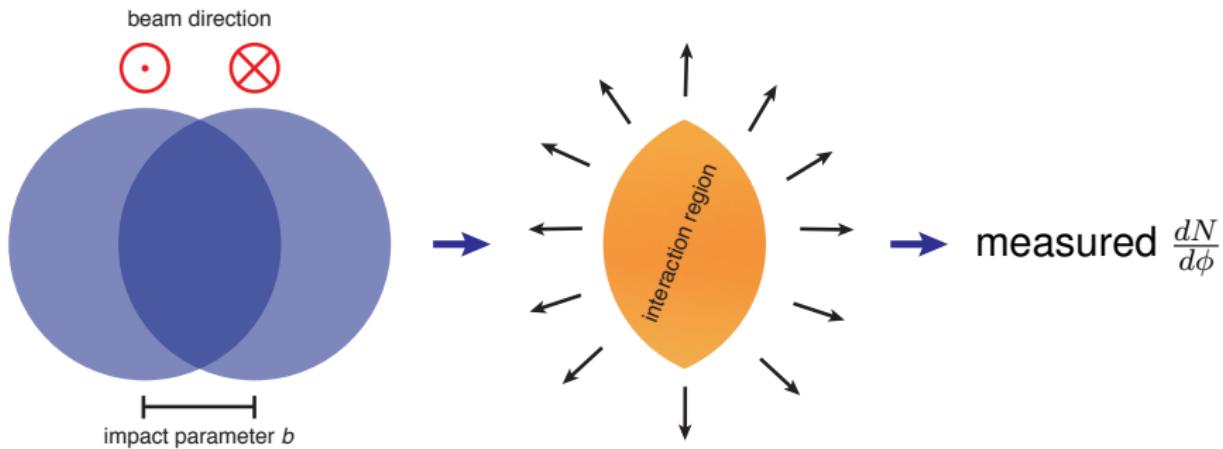


# Introduction - Heavy-ion collisions



# “Flow” in heavy-ion collisions

Study angular distribution of particles perpendicular to the beam

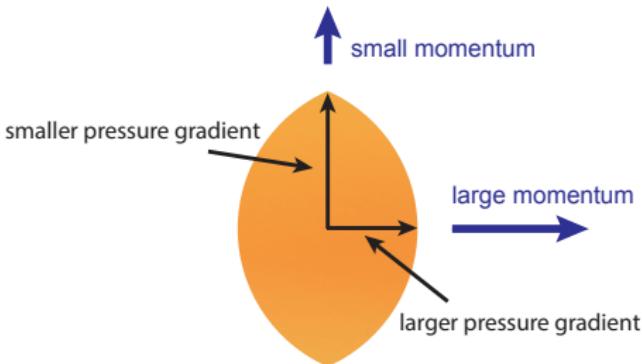
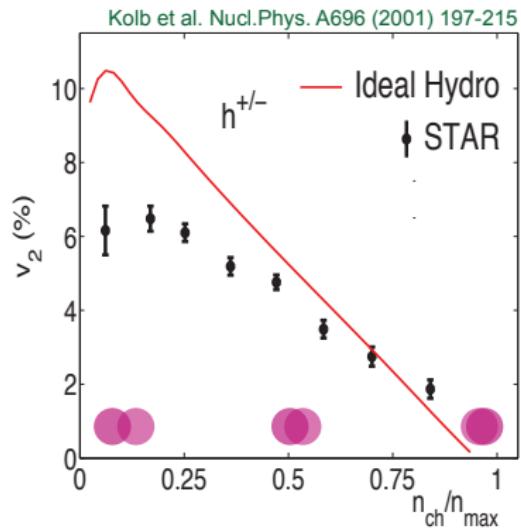


Quantify anisotropy using Fourier decomposition of the distribution:

$$\frac{dN}{d\phi} = \frac{N}{2\pi} \left( 1 + \sum_n (2v_n \cos(n\phi)) \right) \Rightarrow v_2 \text{ characterizes elliptic shape}$$

# “Flow” in heavy-ion collisions

A large anisotropy that depends on the initial geometry was measured



System is strongly interacting

Initial shape is efficiently converted into anisotropic particle flow

System behaves like an *almost ideal fluid*

# Relativistic fluid-dynamics

The initial shape is transformed into the final particle distribution by strong final state interactions, well described by fluid dynamics:  
energy and momentum conservation  
in a system with small mean free path (compared to the system size)

$$\partial_\mu T^{\mu\nu} = 0$$

$$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - Pg^{\mu\nu} + \Pi^{\mu\nu}$$

need additional equation to close the set:

$$\text{Equation of state: } P = P(\epsilon)$$

(comes e.g. from lattice QCD / hadron gas model)

$\Pi^{\mu\nu}$  contains the transport parameters we are after

# Converting energy density to particles: Cooper-Frye

Approximation: Decoupling takes place on **constant temperature** hypersurface  $\Sigma$  at  $T = T_{\text{fo}}$  (some use energy density or even time)

- Number of particles emitted = number of particles crossing  $\Sigma$ :

$$N = \int_{\Sigma} d\Sigma_{\mu} N^{\mu}$$

- We can compute the particle current:

$$\begin{aligned}\Rightarrow N^{\mu} &= \int \frac{d^3 p}{E} p^{\mu} f(x, \partial_{\mu} u^{\mu}) \\ \Rightarrow N &= \int \frac{d^3 p}{E} \int_{\Sigma} d\Sigma_{\mu} p^{\mu} f(x, \partial_{\mu} u^{\mu})\end{aligned}$$

So we get the **invariant inclusive momentum spectrum**  
(Cooper-Frye formula):

$$E \frac{dN}{d^3 p} = \int_{\Sigma} d\Sigma_{\mu} p^{\mu} f(x, \partial_{\mu} u^{\mu})$$

Cooper and Frye, Phys.Rev.D10, 186 (1974)

# Freeze-out in the viscous case

In the viscous non-equilibrium case we need corrections to equilibrium  $f$  to match  $T_{\text{hydro}}^{\mu\nu}$  to  $T_{\text{particles}}^{\mu\nu}$ :

$$f \rightarrow f + \delta f$$

with

$$\delta f = f_0(1 \pm f_0)p^\alpha p^\beta \pi_{\alpha\beta} \frac{1}{2(\epsilon + P)T^2}$$

The choice  $\delta f \sim p^2$  is not unique

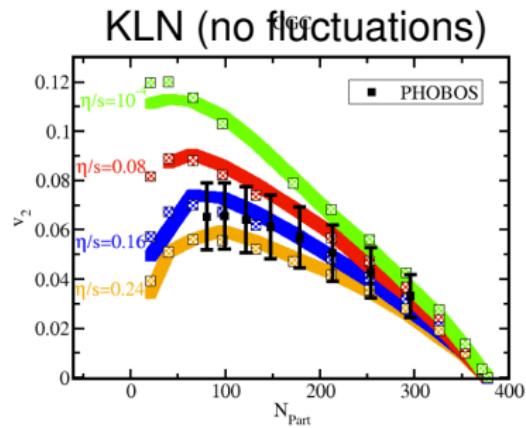
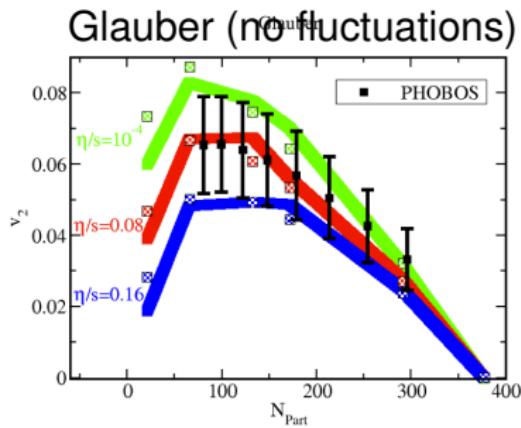
Ambiguity in  $\delta f$  leads to uncertainty

see Dusling, Moore, and Teaney, Phys.Rev.C81:034907 (2010)

The exact form of  $\delta f$  depends on the underlying microscopic theory that is (usually) unknown

# Viscous fluid-dynamics: $v_2$ - Can we determine $\eta/s$ ?

constant  $\eta/s$  Luzum and Romatschke, Phys.Rev.C78:034915 (2008)



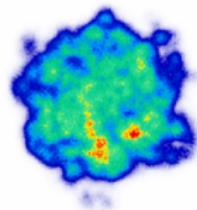
- **Viscosity reduces  $v_2$ :** Diffusion instead of most efficient conversion of spatial into momentum anisotropy as in ideal case
- **Result not conclusive:**  $\eta/s = 0.08$  or  $0.16$  works better depending on (eccentricity of the) initial state: inconclusive

# Initial shape: Event-by-event fluctuations

Initial shape is not smooth but a lumpy blob of energy density

Fluctuating shape affects details of final particle flow

$$\frac{dN}{d\phi} = \frac{N}{2\pi} \left( 1 + \sum_n 2v_n \cos(n(\phi - \psi_n)) \right)$$



With fluctuations: odd harmonics are not zero

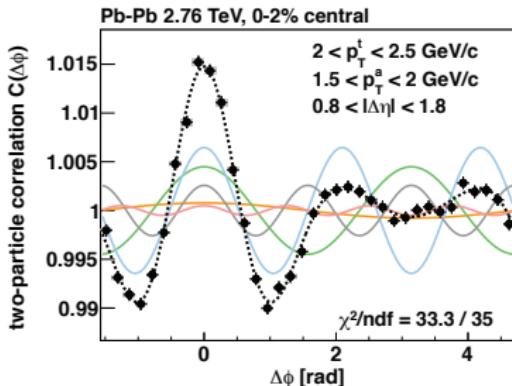
Mishra et al., Phys. Rev. C77, 064902 (2008), Takahashi et al., Phys. Rev. Lett. 103, 242301 (2009)  
Alver and Roland, Phys. Rev. C81, 054905 (2010)

In fact, fluctuations explain entire  
structure of two particle correlations  
(when removing effects from jets)

solid lines:  $v_1, v_2, v_3, v_4, v_5$  term

dashed line: sum

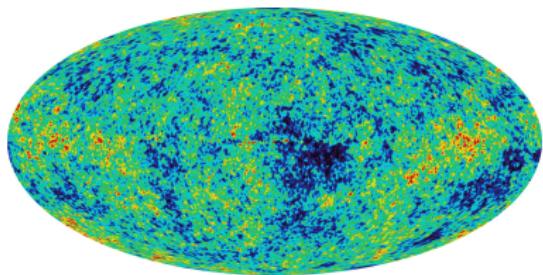
points: correlation measurement



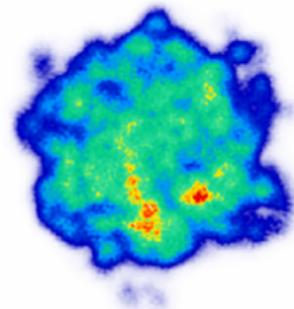
ALICE collaboration, Phys. Lett. B708 (2012) 249-264

# Why the study of fluctuations is so powerful

Analysis analogous to that of the cosmic microwave background (CMB)



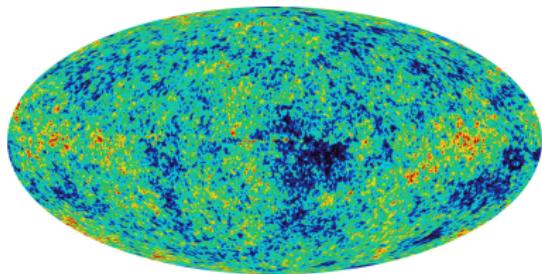
CMB Credit: WMAP Science Team, NASA



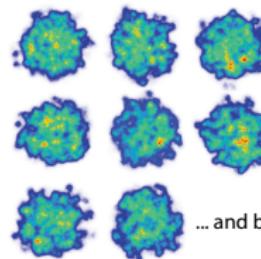
Heavy-Ion Collision

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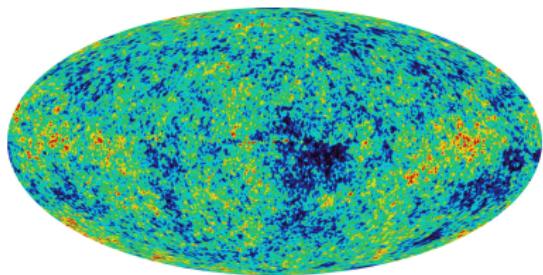
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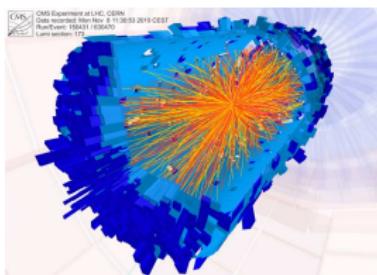
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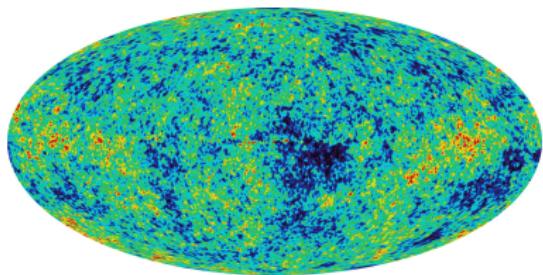
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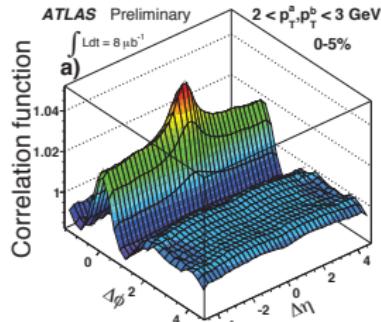
CMS  
Heavy-Ion Collision

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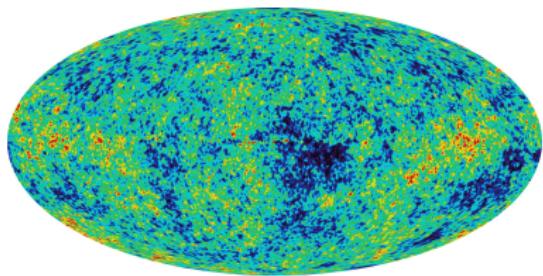
CMB Credit: WMAP Science Team, NASA



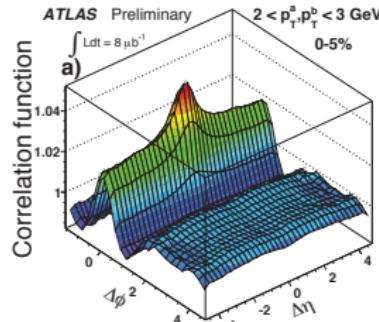
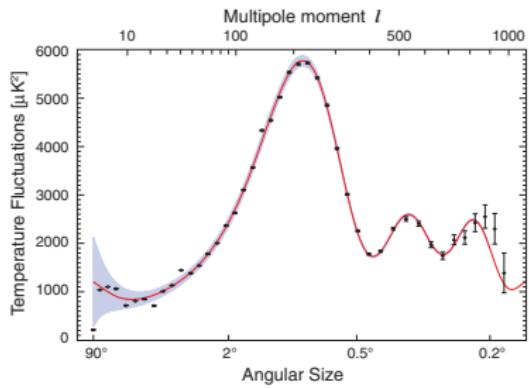
Heavy-Ion Collision

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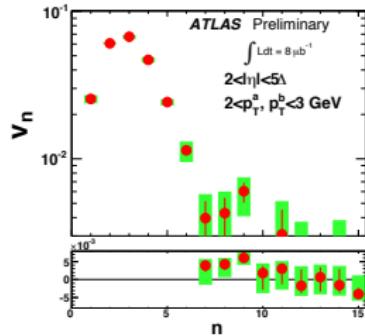
Analysis analogous to that of the cosmic microwave background (CMB)



CMB Credit: WMAP Science Team, NASA

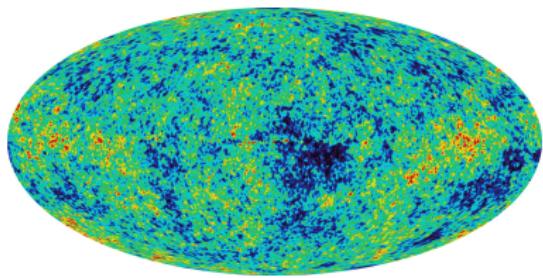


Heavy-Ion Collision

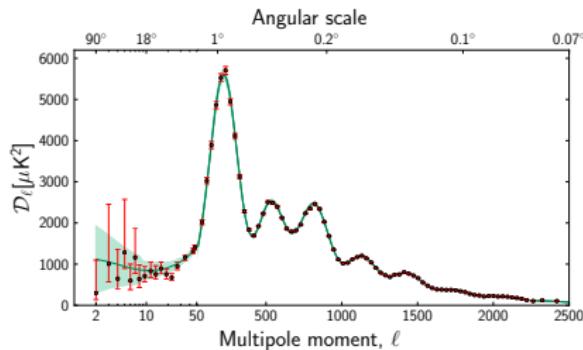


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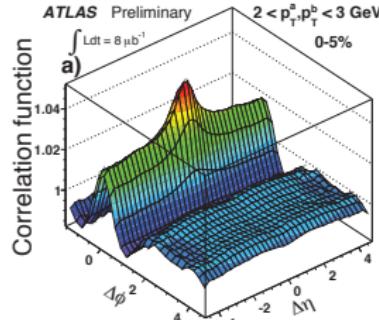
Analysis analogous to that of the cosmic microwave background (CMB)



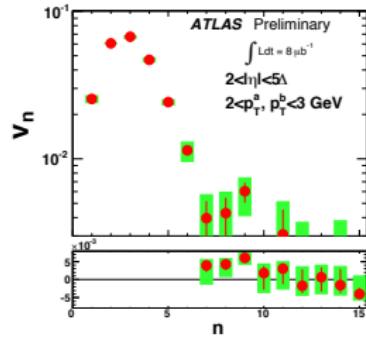
CMB Credit: WMAP Science Team, NASA



Planck collaboration, arXiv:1303.5075



Heavy-Ion Collision



## Viscosity in action

The initial lumpy shape is converted into an anisotropy in the azimuthal particle production via fluid-dynamic expansion

The effectiveness of this conversion is reduced by the system's shear viscosity to entropy density ratio  $\eta/s$

$$\eta/s = 0$$

$$\eta/s = 0.16$$

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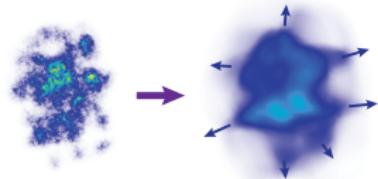
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$$\eta/s = 0$$

$$\eta/s = 0.16$$

# Modeling the initial state

Flow is driven by the initial geometry  
Final result depends on what we start with



That is great news:  
We can actually learn about the initial shape of the colliding system!

We need a rigorous understanding of the initial state to extract  
dynamical properties of the created hot and dense nuclear matter



# Existing initial state models

There are several models of fluctuating initial conditions in HICs

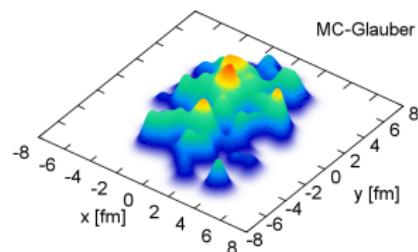
Most commonly used with fluid-dynamic simulations:

Both include geometric fluctuations of nucleons in nucleus

- **MC-Glauber model**

Participants determined from  
nucleon-nucleon cross-section

Gaussian energy density  
assigned to each wounded nucleon

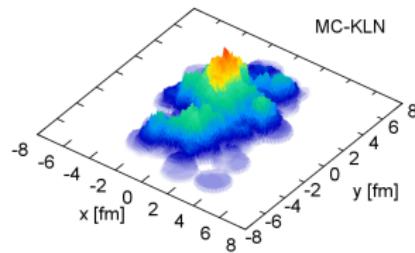


- **MC-KLN model**

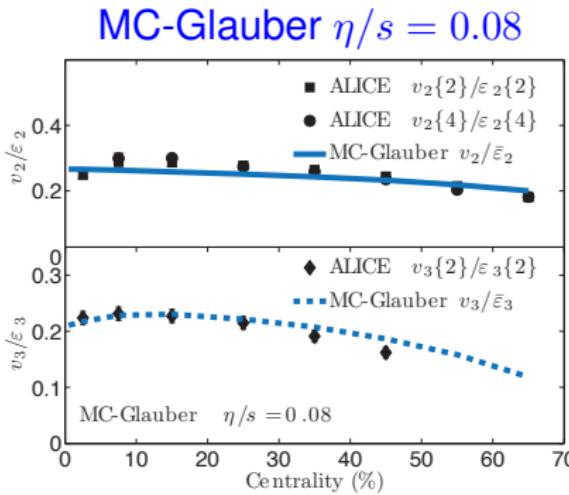
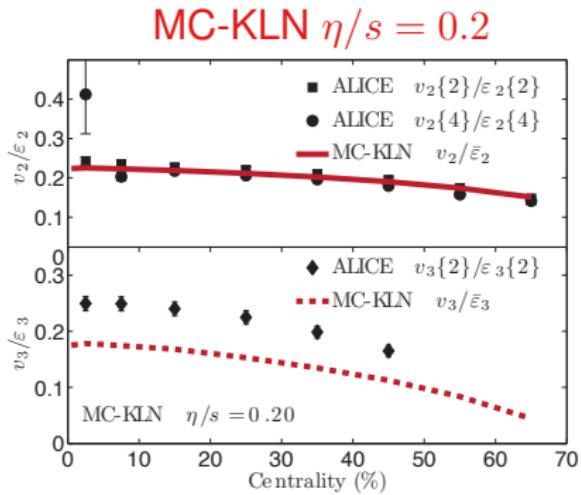
Saturation based model (we'll get to that)

Initial energy density from convolution of  
the two gluon distribution functions

Drescher, Nara, Phys.Rev. C75 (2007) 034905



# Testing initial state models with higher harmonics

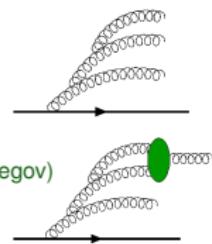


Z. Qiu, C. Shen, U. Heinz, Phys.Lett. B707 (2012) 151-155

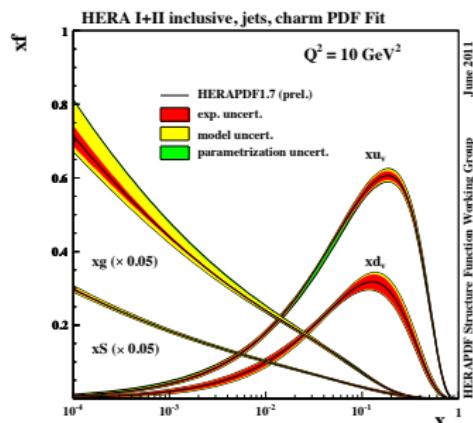
# Nuclei at high energy: Gluon saturation

As we go to higher energy / smaller  $x$ , gluons split, number increases:

**BFKL** (Balitsky,Fadin,Kuraev,Lipatov) equation describes  $x$ -evolution  
but violates unitarity: cross-sections grow without bound



**JIMWLK** (Jalilian-Marian, Iancu, McLerran, Weigert, Leonidov, Kovner) and **BK** (Balitsky, Kovchegov)  
equations include non-linear evolution → saturation



$p_T \lesssim$  saturation scale  $Q_s(x)$ :

- strong saturated fields  $A_\mu \sim 1/g$
- occupation numbers  $\sim 1/\alpha_s$
- ⇒ classical field approximation

Evolution equations determine  $Q_s(x)$

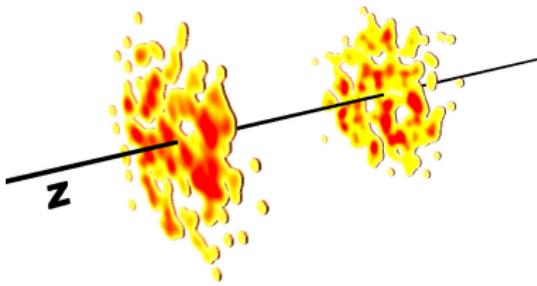
$x$  = longitudinal momentum fraction of partons in a hadron or nucleus

# The IP-Glasma model

Energy and impact parameter  $b$  dependence of  $Q_s(x, \mathbf{b})$   
can be modeled in the **IP-Sat model** Kowalski, Teaney, Phys.Rev. D68 (2003) 114005

Parametrize cross sections for DIS on protons  
and fit to HERA diffractive data  $\rightarrow Q_s(x, \mathbf{b})$

Color charge density is proportional to  $Q_s(x, \mathbf{b})$   
Sample nucleon positions and add all color charge distributions

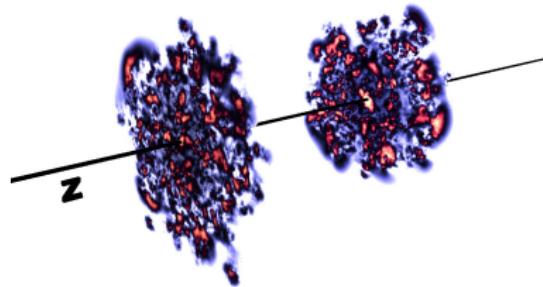


# IP-Glasma: Color charges and gluon fields

Sample color charges  $\rho^a$  from color charge distribution

Color charges determine incoming **color currents**

Solve Yang-Mills equations  $[D_\mu, F^{\mu\nu}] = J^\nu$  for the gauge fields  $A^\mu$



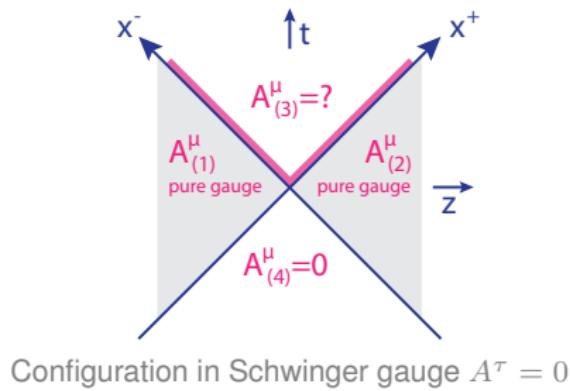
Wilson line correlator shows degree of fluctuations in the gluon fields:  
Fluctuation scale:  $1/Q_s$

Solution after collision:

Kovner, McLerran, Weigert, Phys. Rev. D52, 3809 (1995)

$$A_{(3)}^i|_{\tau=0} = A_{(1)}^i + A_{(2)}^i$$

$$A_{(3)}^\eta|_{\tau=0} = \frac{ig}{2}[A_{(1)}^i, A_{(2)}^i]$$



## Yang-Mills + viscous fluid-dynamic evolution

Energy density and initial flow velocity from  $u_\mu T_{\text{YM}}^{\mu\nu} = \varepsilon u^\nu$   
as input for fluid-dynamic simulation

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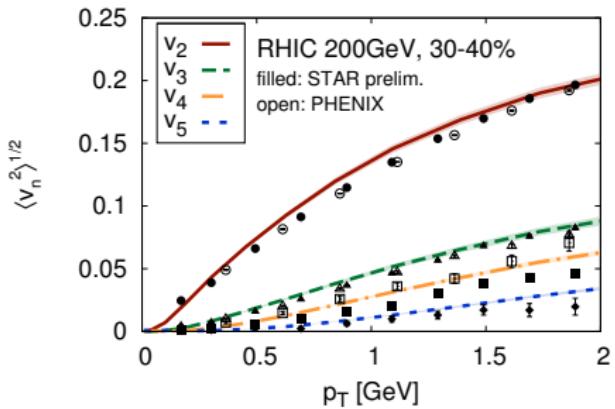
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Viscous fluid-dynamic evolution: MUSIC Schenke, Jeon, Gale, Phys.Rev.Lett.106, 042301 (2011)

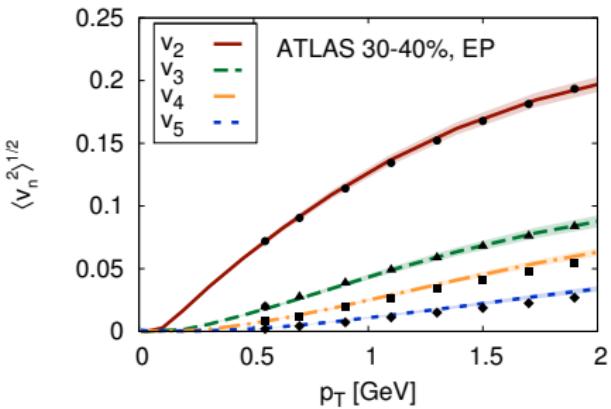
# Viscous flow at RHIC and LHC

C. Gale, S. Jeon, B. Schenke,  
P.Tribedy, R.Venugopalan, PRL110, 012302 (2013)

RHIC  $\eta/s = 0.12$



LHC  $\eta/s = 0.2$



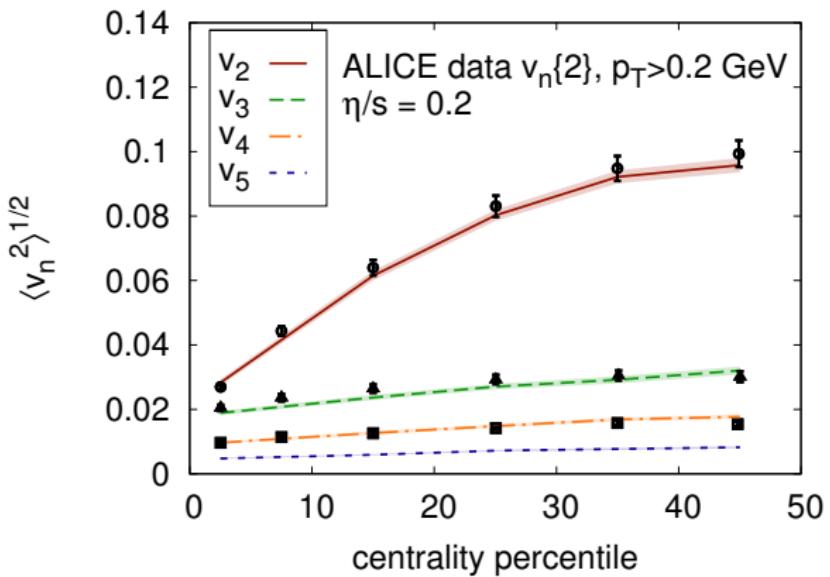
Lower effective  $\eta/s$  at RHIC than at LHC needed to describe data  
Hints at increasing  $\eta/s$  with increasing temperature  
Analysis at more energies can be used to gain information on  $(\eta/s)(T)$

Experimental data:

- A. Adare et al. (PHENIX Collaboration), Phys.Rev.Lett. 107, 252301 (2011)
- Y. Pandit (STAR Collaboration), Quark Matter 2012, (2012)
- ATLAS collaboration, Phys. Rev. C 86, 014907 (2012)

# Centrality dependence of anisotropic flow

C. Gale, S. Jeon, B.Schenke, P.Tribedy, R.Venugopalan, PRL110, 012302 (2013)



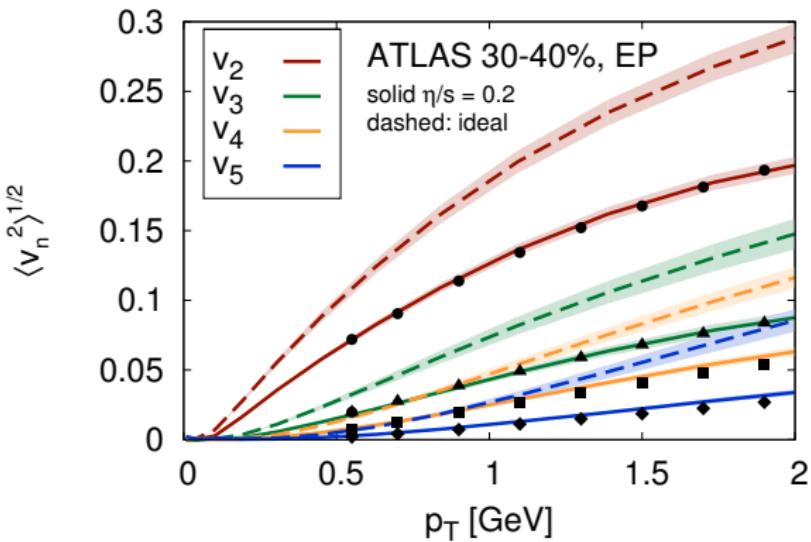
Experimental data:

ALICE collaboration, Phys. Rev. Lett. 107, 032301 (2011)



# What would ideal hydrodynamics give?

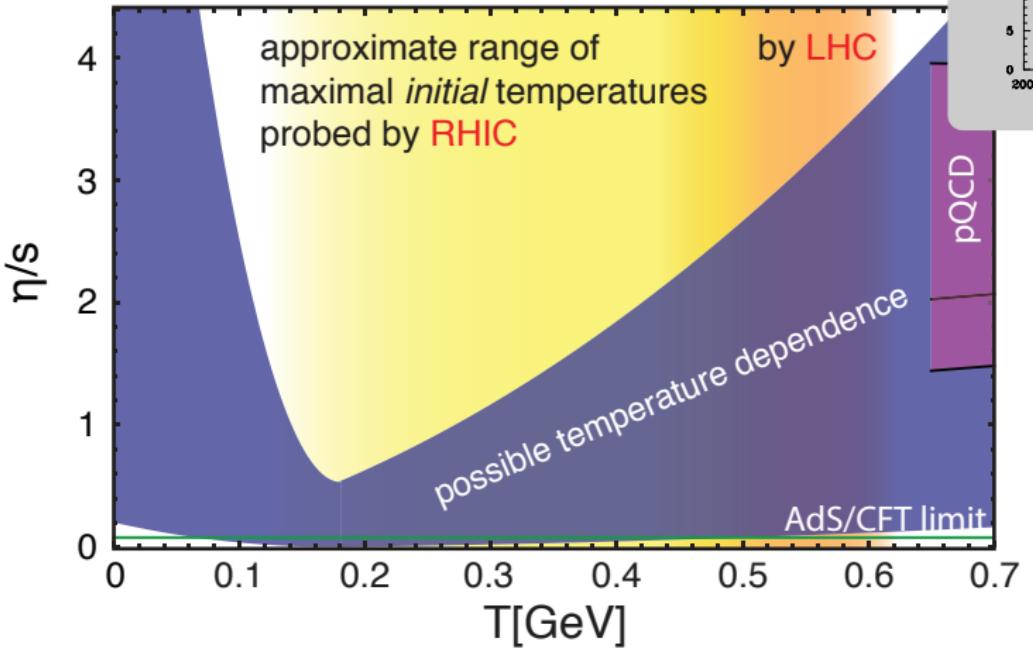
C. Gale, S. Jeon, B.Schenke, P.Tribedy, R.Venugopalan, PRL110, 012302 (2013)



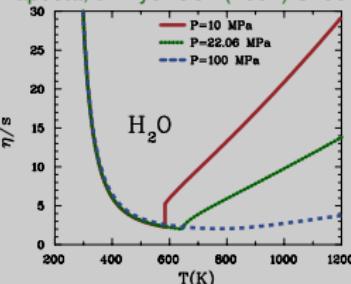
Experimental data:

ATLAS collaboration, Phys. Rev. C 86, 014907 (2012)

# Temperature dependent $\eta/s$



Kapusta, J.Phys. G34 (2007) S295

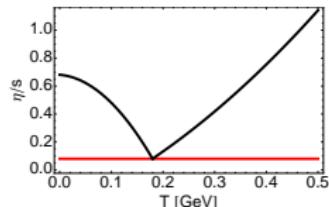


# Temperature dependent $\eta/s$

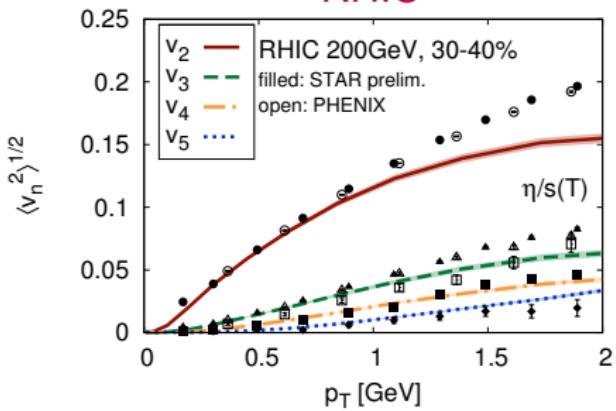
C. Gale, S. Jeon, B. Schenke,  
P.Tribedy, R.Venugopalan, PRL110, 012302 (2013)

Use  $\eta/s(T)$  as in Niemi et al., Phys.Rev.Lett. 106 (2011) 212302

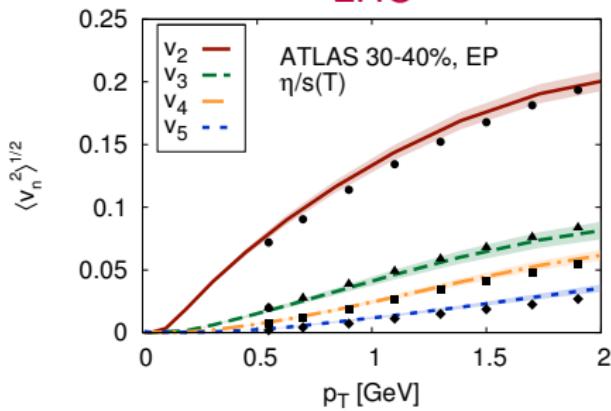
Experimental data: A. Adare et al. (PHENIX), Phys.Rev.Lett. 107, 252301 (2011)  
Y. Pandit (STAR), Quark Matter 2012, (2012)  
ATLAS collaboration, Phys. Rev. C 86, 014907 (2012)



RHIC



LHC



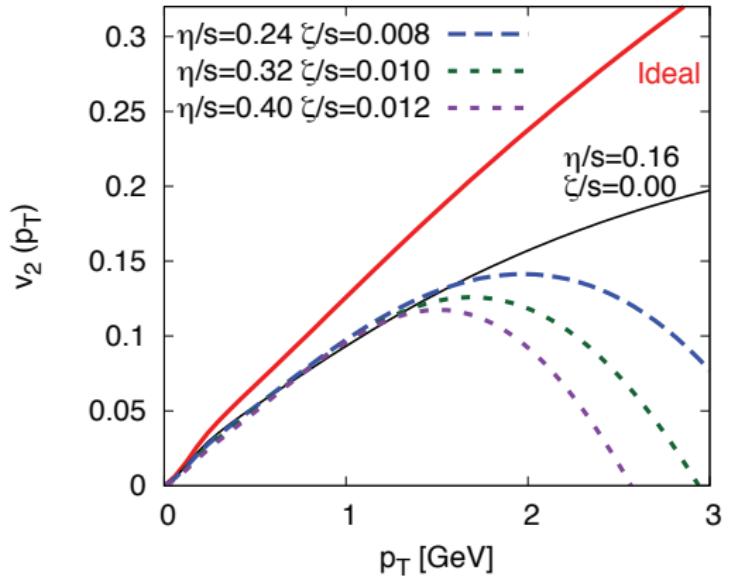
One  $(\eta/s)(T)$  will be able to describe both RHIC and LHC data

Used parametrization not yet perfect: no surprise

More detailed study needed - include different RHIC energies and LHC

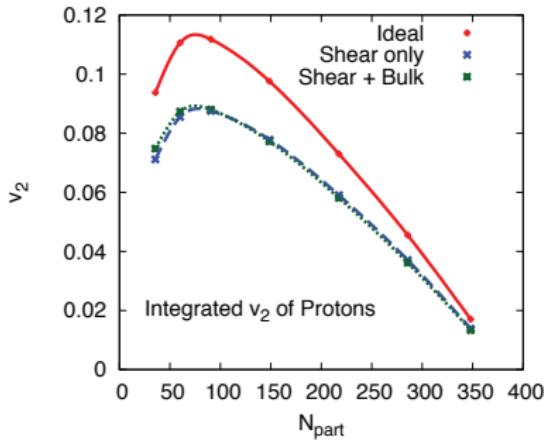
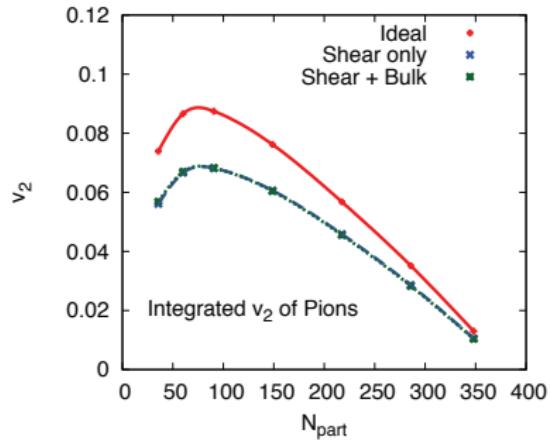
# Bulk viscosity

## Pion elliptic flow



K. Dusling, T. Schäfer, Phys. Rev. C85, 044909 (2012)

# Bulk viscosity

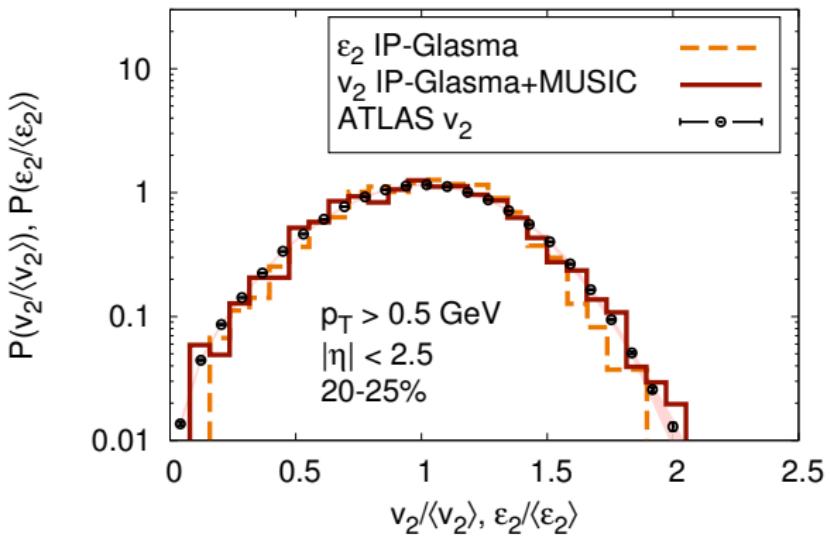


K. Dusling, T. Schäfer, Phys.Rev. C85, 044909 (2012)

using  $\eta/s = 0.16$  and  $\zeta/s = 0.005$

# Event-by-event distributions of $v_n$

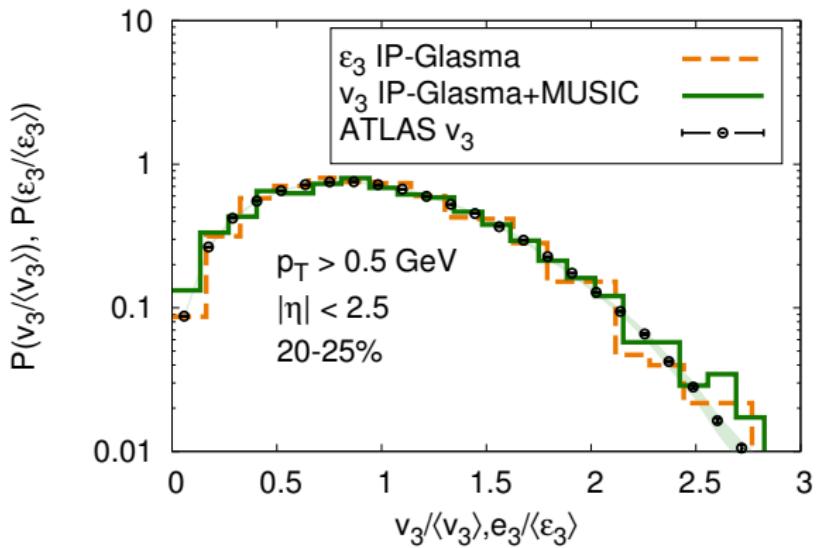
Experimental data: ATLAS collaboration, arXiv:1305.2942



C. Gale, S. Jeon, B. Schenke, P. Tribedy, R. Venugopalan, PRL110, 012302 (2013)

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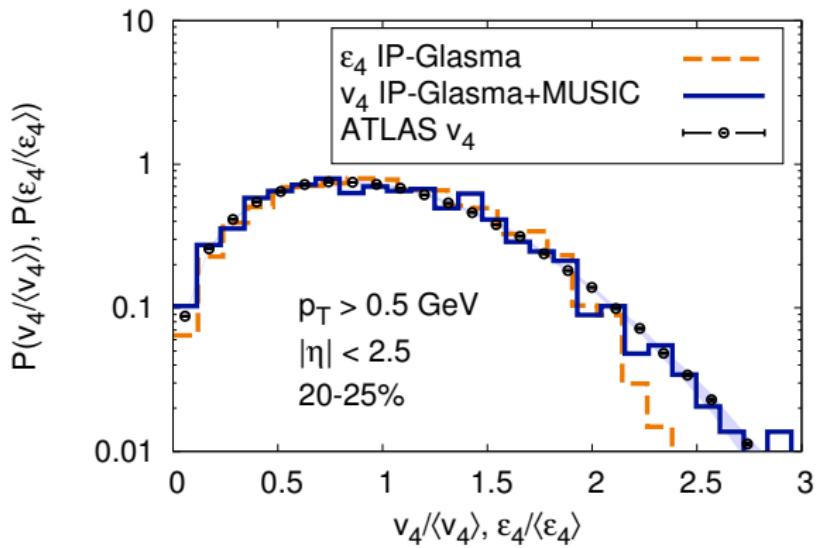
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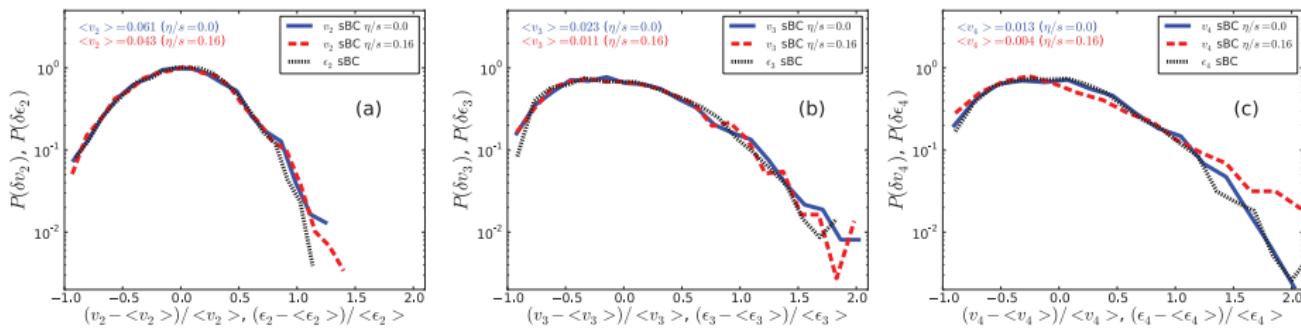
C. Gale, S. Jeon, B.Schenke, P.Tribedy, R.Venugopalan, PRL110, 012302 (2013)

# Scaled distributions nearly independent of $\eta/s$

Black: Eccentricity distributions

Blue:  $v_n$  distributions with  $\eta/s = 0$

Red:  $v_n$  distributions with  $\eta/s = 0.16$



H. Niemi, G.S. Denicol, H. Holopainen, P. Huovinen, Phys.Rev. C87, 054901 (2013)

Independent handle on initial state

## Summary and conclusions

- Analysis of anisotropic flow yields information about the initial shape and transport properties of heavy-ion collisions
- Higher flow harmonics constrain initial state model
- Color-Glass-Condensate initial state and viscous fluid dynamics describe experimental data very well
- Effective shear viscosity at RHIC smaller than at LHC
- Studying heavy-ion collisions at different energies can yield information on temperature dependence of  $\eta/s$  and other transport properties
- Bulk viscosity needs more detailed study
- Flow fluctuations yield medium independent information on the initial state

# BACKUP

# Effect of $\delta f$

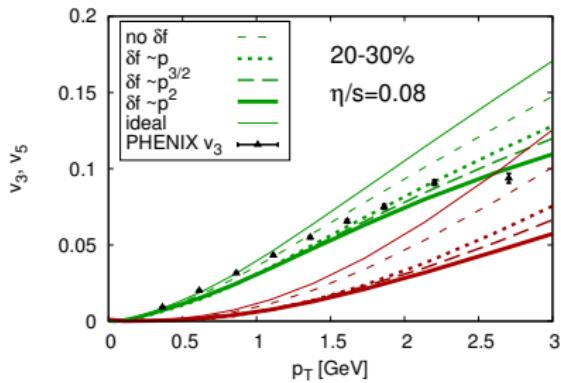
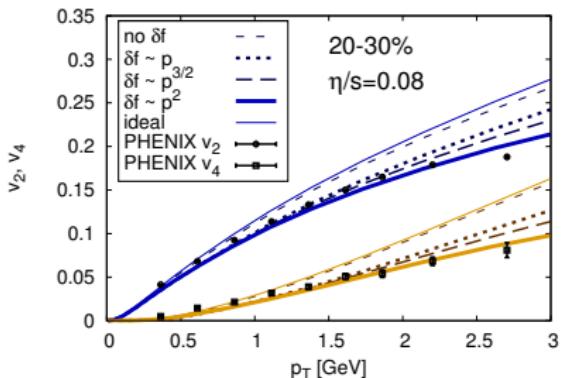
Remember:  $\delta f = f_0(1 \pm f_0)p^\mu p^\nu \pi_{\mu\nu} \frac{1}{2(\epsilon + \mathcal{P})T^2}$

The choice  $\delta f \sim p^2$  is not unique.

More generally: from using different energy dep. of relaxation time

$$\delta f = \frac{120}{\Gamma(6 - \alpha)} f_0 (1 \pm f_0) \left( \frac{T}{E} \right)^\alpha p^\mu p^\nu \pi_{\mu\nu} \frac{1}{2(\epsilon + \mathcal{P})T^2}$$

with  $\alpha \in [0, 1]$ .



below 2 GeV: weak dependence

# Theoretical description: Viscous fluid dynamics

Evolution of the system described by fluid dynamics:  
effective theory for the low momentum modes  
valid for a strongly interacting system

$$\partial_\mu T^{\mu\nu} = 0$$

$$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - Pg^{\mu\nu} + \pi^{\mu\nu}$$

need additional equation to close the set:

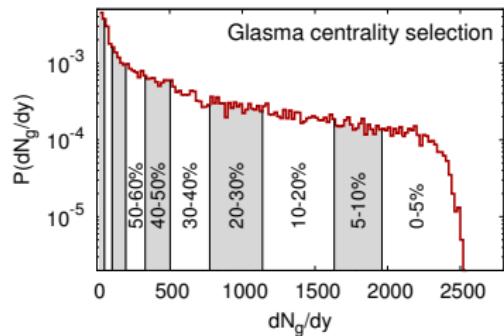
**Equation of state:  $P = P(\epsilon)$**

(from lattice QCD / hadron gas model)

$\pi^{\mu\nu}$  contains dissipative effects

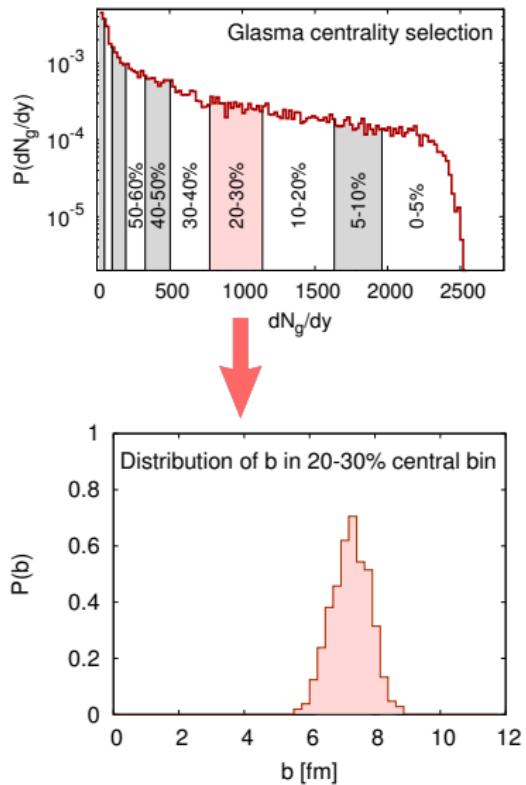
# Viscous flow at LHC

C. Gale, S. Jeon, B.Schenke, P.Tribedy, R.Venugopalan, PRL110, 012302 (2013)



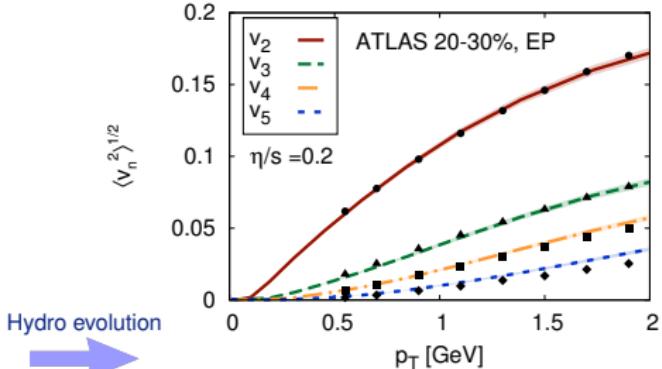
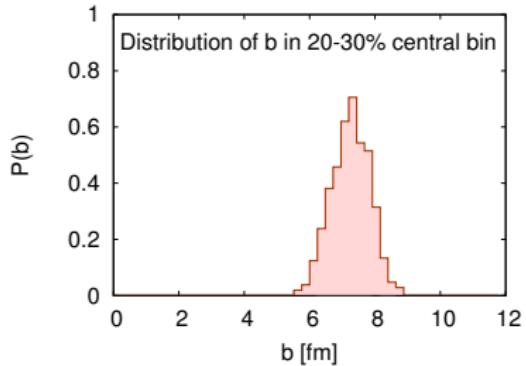
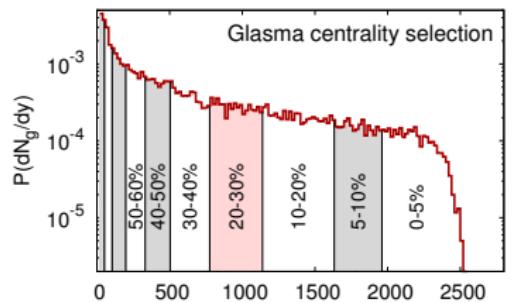
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# Viscous flow at LHC

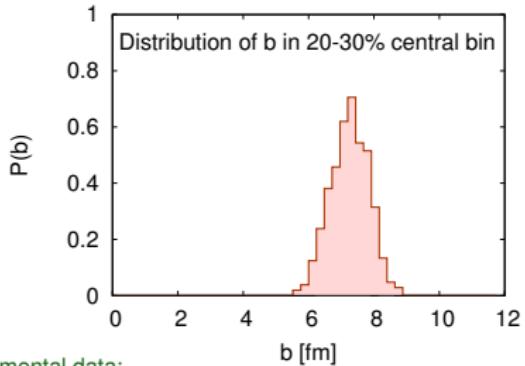
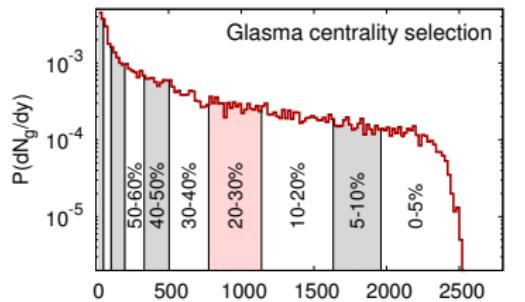
C. Gale, S. Jeon, B. Schenke, P. Tribedy, R. Venugopalan, PRL110, 012302 (2013)



Hydro evolution  
MUSIC

# Viscous flow at LHC

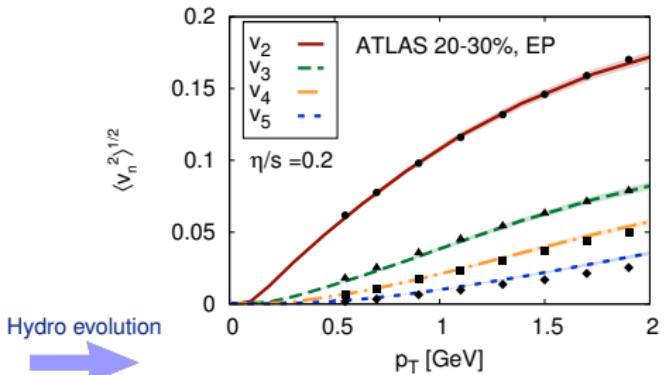
C. Gale, S. Jeon, B. Schenke, P. Tribedy, R. Venugopalan, PRL110, 012302 (2013)



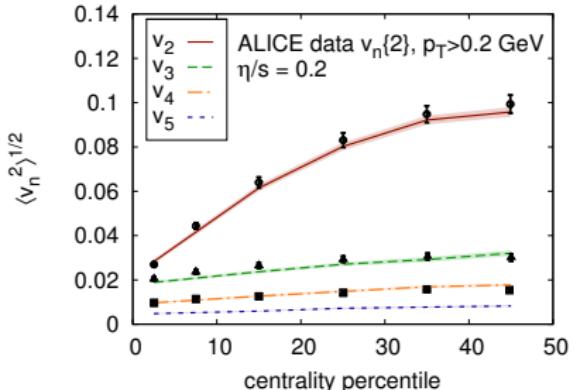
Experimental data:

ATLAS collaboration, Phys. Rev. C 86, 014907 (2012)

ALICE collaboration, Phys. Rev. Lett. 107, 032301 (2011)



Hydro evolution  
MUSIC

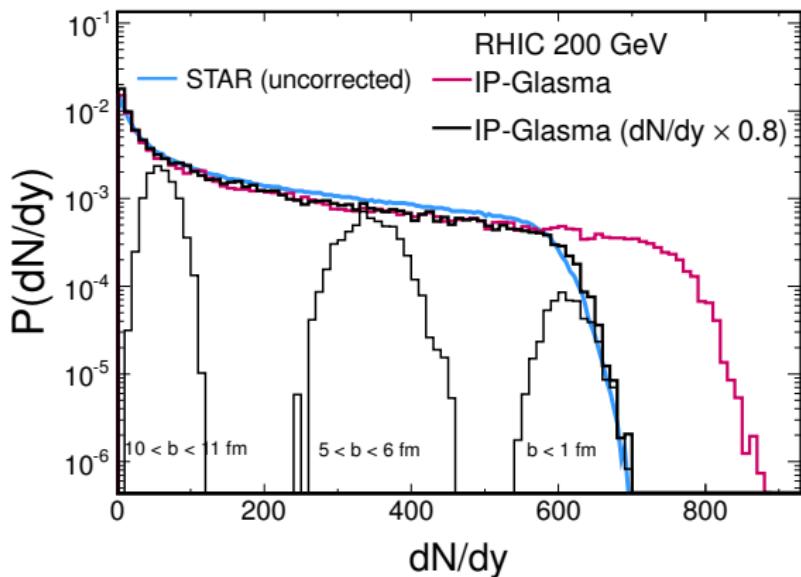


# Multiplicity

B.Schenke, P.Tribedy, R.Venugopalan, Phys. Rev. C86, 034908 (2012)

$P(dN_g/dy)$  at time  $\tau = 0.4$  fm with  $P(b)$  from a Glauber model

Experimental data: STAR, Phys. Rev. C79, 034909 (2009)

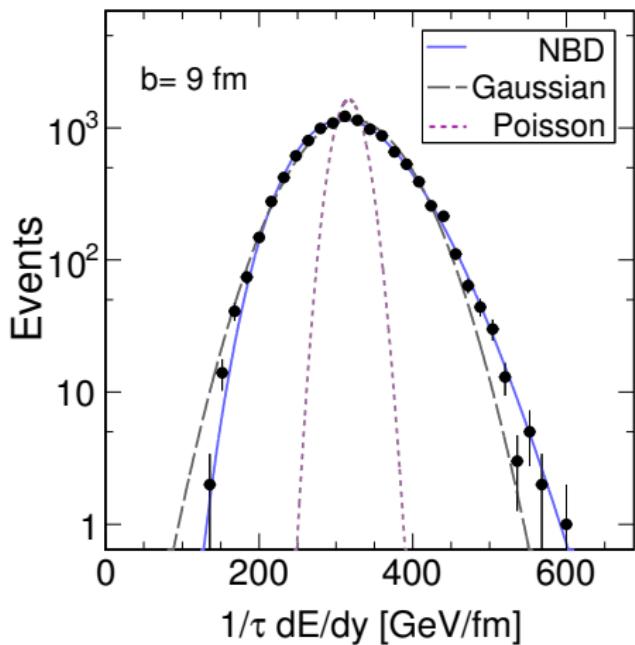


Glasma model gives a convolution of negative binomial distributions  
No need to put them in by hand

# Negative binomial fluctuations

B.Schenke, P.Tribedy, R.Venugopalan, Phys.Rev.Lett.108, 252301 (2012)

Fluctuations in the total energy per unit rapidity produce negative binomial distribution (NBD).



$$P(n) = \frac{\Gamma(k+n)}{\Gamma(k)\Gamma(n+1)} \frac{\bar{n}^n k^k}{(\bar{n}+k)^{n+k}}$$

Good, since multiplicity in pp collisions can be described well with NBD.

In AA, convolution of NBDs at all impact parameters describes data well too.

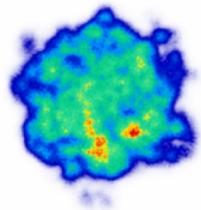
P. Tribedy and R. Venugopalan  
Nucl.Phys. A850 (2011) 136-156

MC-KLN does not do that - these fluctuations need to be put in by hand.

see Dumitru and Nara arXiv:1201.6382

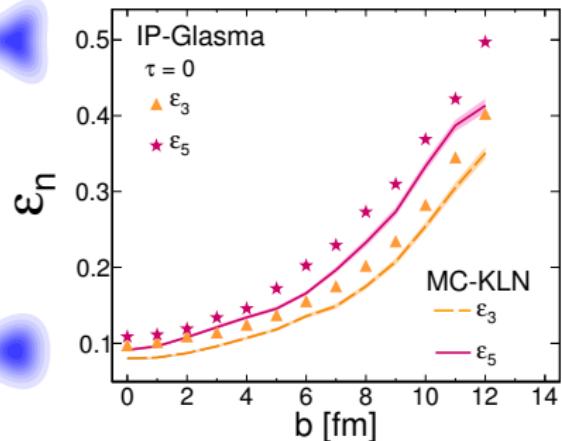
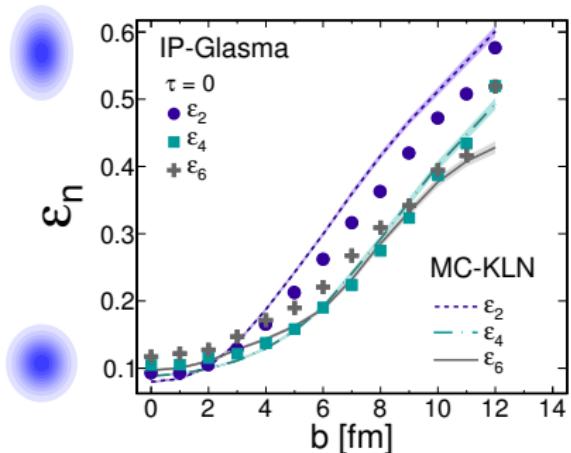
# Eccentricities

B.Schenke, P.Tribedy, R.Venugopalan, Phys.Rev.C86, 034908 (2012)



Characterize the initial distribution by its ellipticity, triangularity, etc...

$$\varepsilon_n = \sqrt{\langle r^n \cos(n\phi) \rangle^2 + \langle r^n \sin(n\phi) \rangle^2} / \langle r^n \rangle$$

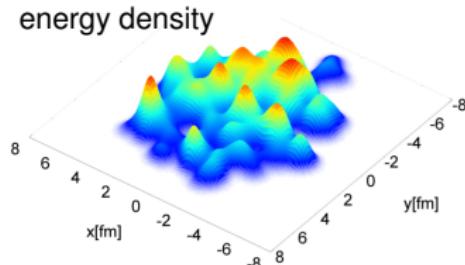


- $\varepsilon_n$  larger in Glasma model for odd  $n$
- $\varepsilon_n$  smaller in Glasma model for  $n = 2$  (for  $b > 3$  fm)  
about equal for  $n = 4$ , larger for  $n = 6$

# MUSIC: studying the effect of viscosity and fluctuations

- **Setup:**

Wounded nucleons are assigned a Gaussian energy density distribution width  $\sigma_0$  is a free parameter



- **Evolution:**

Hydrodynamic evolution with shear viscous effects

System expands, becomes dilute, freezes out

Initial spatial anisotropy is transformed into momentum anisotropy

- **Energy density → Particle spectra:**

Cooper-Frye formula:

$$E \frac{dN}{d^3p} = \int_{\Sigma} d\Sigma_{\mu} p^{\mu} f(T, p_{\mu} u^{\mu}, \pi^{\mu\nu})$$

followed by resonance decays

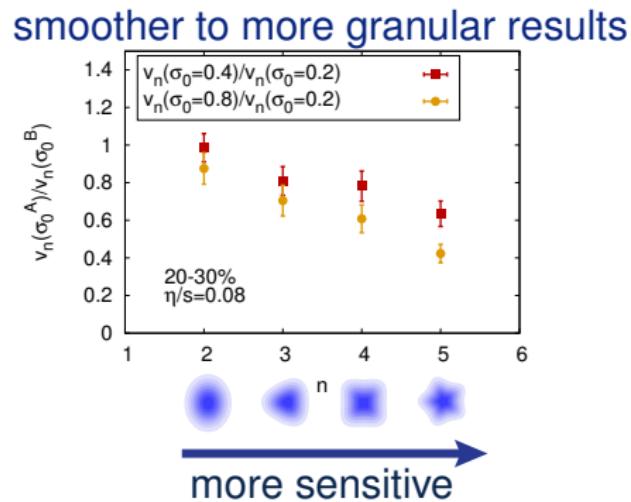
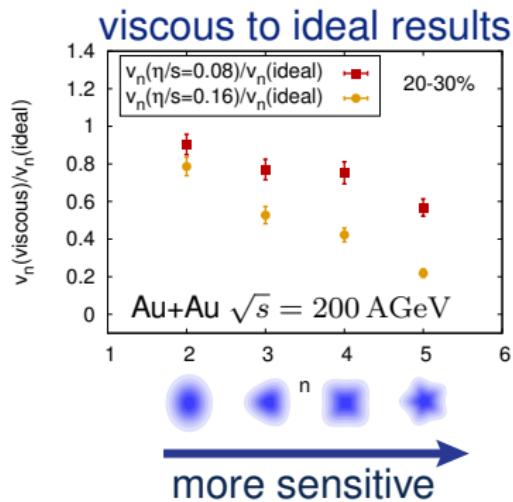
$\Sigma$  = freeze-out surface (surface of constant temperature)

$f$  = particle distribution

Cooper and Frye, Phys. Rev. D10, 186 (1974)

# Sensitivity of $v_n$ on viscosity and fluctuations

B. Schenke, S. Jeon, C. Gale, Phys.Rev.C85, 024901 (2012)

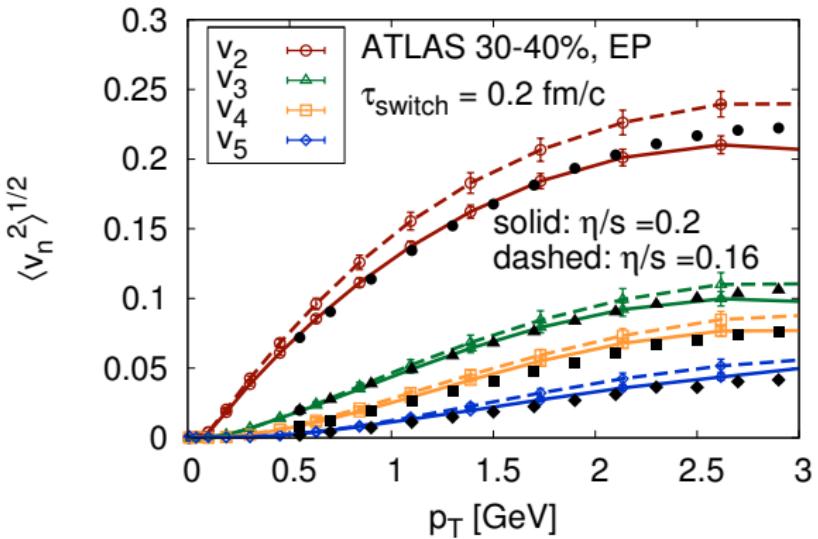


Viscosity decreases anisotropic flow (it's friction)

Smoothen initial conditions decrease anisotropic flow

Sensitivity to viscosity and initial state structure increases with  $n$

# Smaller average $\eta/s$



Using  $\eta/s = 0.16$  overestimates all  $v_n$

Experimental data:

ATLAS collaboration, Phys. Rev. C 86, 014907 (2012)